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Traffic Signal Control System with Extended Logic in the Context of the Modal Split

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Abstract

The paper is presents the discussion on the concept of extending the logic of the traffic signal control algorithms at the road intersections with additional decision making criteria. Currently typical traffic signal control logic at an signalised intersection is usually based on the measurements of the cross-section characteristics of traffic at detector on intersection approach or in a broader case over the approach area of the controlled object. The traffic control criteria are therefore only partial descriptive characteristics of the traffic. These authors point out the existing problem of the balancing of supply and demand for the usage of a road network, in the context of traffic organisation and management. A modification of the F.V. Webster's formula has been presented as an example of an application of the proposed control logic. In alignment with the contemporary policy of the sustainable development of the transportation this problem has been complemented with the discussion on influencing the modal split. The presented extended logic of traffic signal control at the intersections is therefore predestined to utilise optimally both the spatial potential of road networks (their capacity) as well as their modal split.

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Keywords: ATCS, traffic control systems, road network capacity, Webster formula, supply and demand in road networks, traffic detectors

Nomenclature

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T	optimal cycle length time [s]
L	total lost time during a cycle [s]
y_i, Y	saturation ratio of critical movements, $y_i=(Q/S)_i$, sum of flow ratios of critical movements
Q	traffic flow
S	saturation flow
RNC_{Vc}	Road Network Capacity (signalised intersection) [Veh.]
V_c	average approach communication speed [km/h]
L_c, L_v	total length of road network (signalised) and average length of vehicle in network [m]
t_h	headway [s]
μTCS, PI	traffic control system efficiency [%], performance index [-]
TO,TM	traffic organization [-], traffic management [-]
G_i, G_e	green time for i-phase [s], effective green time [s]
Σt_i	the change interval lost time [seconds per i-phase]
rb_{ckl}(L)	road network capacity at next link, behind intersec. (L-Left-Turn phase), R-Right,S-ahead etc.
$rb_{ckl}(\mathrm{L})_{(max)}$	– maximum road network capacity at (i) movement direction
m	numbers of streams in lanes, signal groups (left, rights turning vehicles etc.)

1. Introduction

Most of the popular algorithms of traffic signal control systems regardless of the type of signals applied (TCS type: Pretimed, Semi-actuated, Fully Actuated etc.) base their operating logic on the measurement of the traffic parameters at the intersection approach (approach area) of the controlled object. The measured quantities are: traffic flow, lengths of queues, an occupancy of a road section and many others. A cycle length determined using the most popular traffic signal control algorithms (F.V. Webster formula of 1958) depends on the saturation flows at individual approach being the products of the traffic intensity flows and the saturation rates.

$$T = \frac{1{,}5 \cdot L + 5}{1 - \sum_{i=1}^{n} y_i} \tag{1}$$

A large number of methodical solutions based on the Formula (1) have been derived by extending and modifications to the Formula. These solutions are used in the practically applied traffic signal control algorithms functioning at signalised intersections. It is worth mentioning that these are predominantly the control solutions based on measurements of demand characteristics (such as the request for access to specific segments (links) of the road network). Very often the measurements of characteristics of approach streams (the demand) are taken at discrete cross-sections of the read network (the instantaneous and estimated demand). In reality, the demand for the access to a road network is characterised by a high dynamics and its distribution is non-uniform in time and space. The traffic signal control algorithms at the signalised intersections can offer a certain supply by means of regulating the length of the permission signal (green light) assigned to specific traffic streams requesting access to specific segments of the road network. Therefore, the access time to the network assigned to individual users may be the measure of a supply characteristic. The demand is identified in relation to the road network space and the supply is related to the handling time of traffic streams. In case of the processes describing the demand at the intersection approach the time measurement is possible but it is secondary to the spatial parameters. In turn, the measurement/setting of the time lost within a cycle of the traffic signals is a consequence of the fixed parameters of the point infrastructure and of the previous stages of the programming of the traffic control system. With such an approach, influencing the supply characteristics should by definition optimise the access to the road infrastructure. In case of the ATCS area control the management of the supply of a road network is usually related to the operating parameters of the weakest approach in the system (i.e. an intersection with the worst traffic conditions). A specific synthetic key performance index (KPI) is often calculated and then used to manage the whole of the road network. The KPI is often assumed to be a loading of a signals group, of an approach or of the whole intersection with the worst traffic conditions. The Highway Capacity Manual (HCM) 2010 suggests base saturation flow rate based on factors such as: movements, numbers of pedestrians, lane width, street parking etc. With this approach the supply of a traffic signal control system of a single intersection leads to the optimisation of both supply and demand before the traffic signal control system elements (signal heads). A control is applied always to the approach of the controlled object. Classic control is therefore an example of balancing the supply and the demand in the request channel with no additional network parameters taken into account. Such a type of networks may be compared to a maze which cannot be accessed despite a free space being available within (or with the access being limited despite of the existence of free resources). In case of symmetrical distributions of the traffic streams within the network and of their homogeneity in time and space such an approach may be rational (the traffic characteristic levelling along streams takes place then). Unfortunately, the road traffic is a stochastic and self-regulating process and the spatial distributions of its characteristics both at the level of traffic streams and traffic flows are neither homogeneous nor symmetrical.

In a basic signal control system (two, three etc. traffic lights in a row) the balancing of the supply with the demand is performed only on the basis of the data at the approach of the each signal heads in signal control system. In the road traffic signal control systems an optimisation of traffic over large parts of the network is assumed to take place due to the co-ordination (progression) of traffic controllers. From this angle point it is interesting to notice that the traffic signal control is achieved over two spaces. In case of the demand measured it is the space of the road network concerned and in case of the supply offered it is the operating time of the road network. This is a case of a specific dichotomy of traffic control systems. The division of the control logic of these systems concerns the boundaries for variable time and distance parameters and the areas before and ahead the traffic lights (signal heads). The problem is significant as this fault of control systems is related to the partial knowledge of the condition of a road network. A co-ordination of signal control at neighbouring intersections does not solve this issue to a sufficient degree: in such a case these are still the traffic streams before the synchronised traffic lights (or their groups) that are controlled and co-ordinated. The availability of space within the road network is not controlled at all (also control, but in other purposes at upstream for the next intersection cycle optimisation). This is an big issue if empty space exists behind a signal head. The research problem may therefore be formulated as a question: should the queues be offloaded according to their characteristics or should the traffic be optimised taking into account the available road network space (network capacity)? In the latter case the problem is the estimation of the available space (capacity) in the road network (signalised net only). Installing traffic detectors along whole length of the traffic lanes and over the whole area of the network is not economically justified. Each road network has a specific road network capacity. The road network capacity (*RNC*) may be expressed as a number of vehicles contained (or which may be) at the same time on each available traffic lane and the collision area of an intersection. Vehicles being parking can also be accounted for (by taking into account the car parks). The magnitude of the road network capacity of a road network is strongly dependent on the communication speed, the total length of all the lanes as well as on such parameters as a average length of vehicles, mean gap between the vehicles, the efficiency of the control system, traffic organisation, traffic management, behaviours of drivers (driver model), flow structure, etc.

In case of whole road network within city limits, the determination of the road network capacity may encounter a number of computational problems. However, as the length of network sections for which the capacity is estimated, decreases (inter nodes dist. $\Delta S \rightarrow 0$), the accuracy of the determination of the road network capacity improves (variations of this values decreases). In theory, in case of short sections of traffic lanes connecting subsequent intersections, calculation of the relevant transportation capacities should not be technically difficult. For this purpose, each lane should be equipped with a measurement instrument (a recorder) able to estimate the speed of the vehicles, section travel times. In case of classic detectors they should be mounted upstream at the approach right after the preceding intersection (but for other purposes then in SCOOT systems). In case of CCTV cameras they may be mounted downstream, at the entries directly at the intersections or alternatively at the exits from the intersection. A measurement diagram illustrating the measurement and estimation of the road network capacity of a road network is shown in Figure 1.

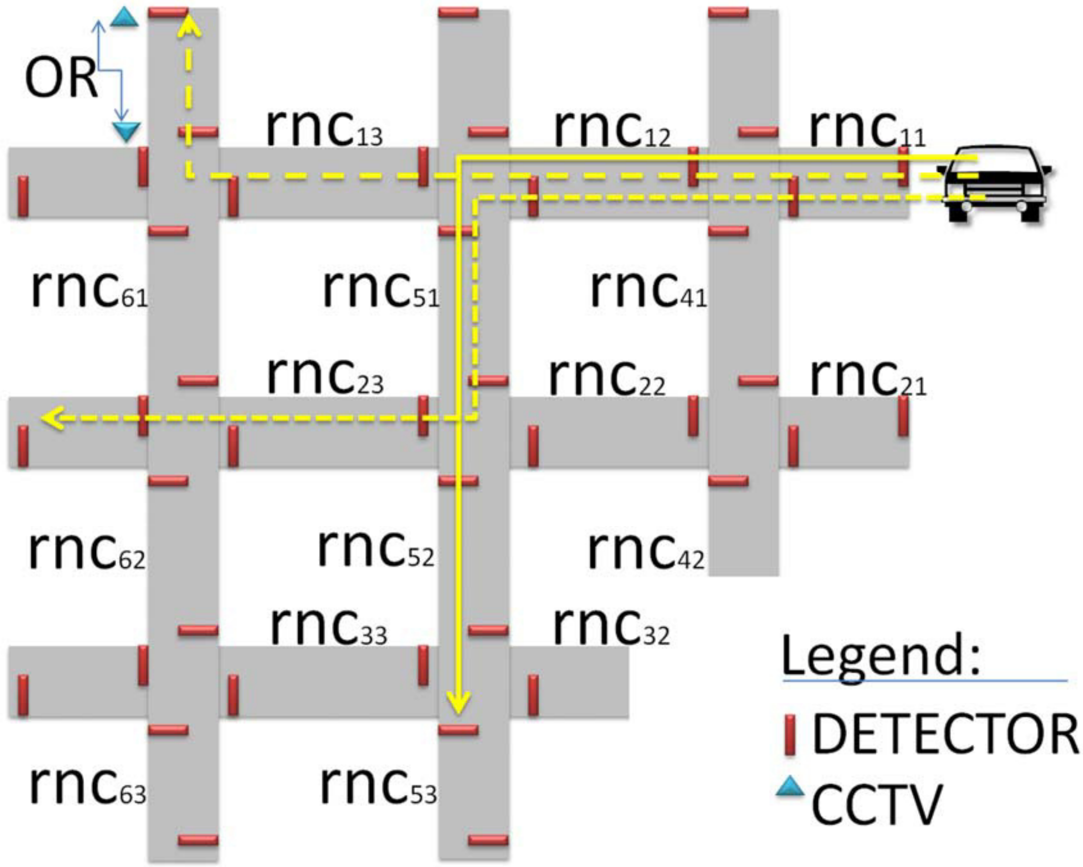

Fig. 1. Measurement system for *RNC*. Source: own elaboration.

The extension of a detection subsystem of a traffic control system is highly problematic. Doubling the detection system the control system gets a functionality of monitoring of the road network capacity of a road network practically over the whole area of an ATCS. It is estimated that the cost of ATCS is in this case increased by around a 10-20 % while its functionality is nearly doubled. In such a system, each detector/traffic recorder records the road network capacity rbc_{ij} , where i is a unique road number within a network and j is a single section of that road (usually a single lane) connecting traffic light controlled intersections. In dense networks with small inter-nodes distances most probably only a single recorder per inter-nodes section is sufficient. In the road network well investigated by these authors (a dense network) mean inter-nodes distances (typical city area) vary from 50 to 250 metres. From the viewpoint of the methodology used in this paper such distances may be covered by a single traffic recorder.

2. Methodology

Past the traffic light (looking in the direction of the potential routes to be taken by the vehicles before the signal heads) there exists a potential supply (a road network capacity) of the road network which is not rationally utilised due to the insufficient information detection subsystem of the control system. In the Webster's model the formula used to calculate the length of a green signal in the *i-th* phase is (Webster, 1958):

$$G_i = \frac{y_i}{Y} \cdot \left(T - \sum_{i=1}^{n} t_{mi} \right) \tag{2}$$

With the proposed modification of the measurement system in a road network with traffic light signal control, a modification of the formula (1) and (2) is being proposed. The formula (1) should also take into account the cases when a sufficient road network capacity ahead of the signal head does (or does not) exist. The length of the green signal determined by optimising the length of the signal cycle should allow a differentiation of these two situations. In the currently operating systems it is only the traffic conditions before the traffic lights that are differentiated [HCM, SIIG, MUTCD]. On a 4-approach intersection this requires taking into account sets of up to three values $\{rbc_{ij}\}$ (road network capacity of the *j-th* links). In this sense, the equation (1) may be modified by substituting, instead of the degree of saturation on critical lanes $y_i = (Q/S)_{(i)}$ a formula modified with the following expression:

$$y_i = \frac{\left(\frac{Q_i}{S_i} + \left(\frac{rbc_{kl}^{(L)} + rbc_{kl}^{(S)} + rbc_{kl}^{(R)}}{\sum rbc_{kl}^{\max(L,S,R)}} \right) \right)}{2^*} \tag{3}$$

Such an operation allows taking into account in Formula (1) a possibility of a smooth exit ahead of a traffic light. In formula (3) upper index (*) means than 2^* may be replaced by weighted average. In this sense the green intervals of individual signal groups should be modified in case of a lack of space ahead of a traffic light or this space being insufficient. It is more beneficial to extend (or to shorten or otherwise modify) the green interval in this particular signal group which at a specific instant has more convenient conditions of continuing the movement in the network. With this approach it is of a bigger importance how much of a free space will remain available from the point of view of the preceding traffic light rather than when the stream will reach the next node with light signal control, i.e. the share in the cycle length will also take into account the parameters of the road network ahead of the traffic lights. The degree of saturation in Formula (3) has been complemented with the degree of utilisation of the road network capacity of a lane ahead of the signal heads. A weighted average (*) or an arithmetic (3) of the degree of saturation and the degree of utilisation of the road network capacity is taken in formula (1). In this way the area over which the optimisation of the traffic streams takes place includes also the lane ahead of the traffic light (specifically its parameter of the road network capacity). With a road network equipped in a way shown in Figure 1, the methodology represented by the Formula (3) may be extended over the next segments of the network, etc.:

$$y_i = \frac{1}{4} \cdot \left(\left(\frac{Q_i}{S_i} + \sum_i^n y_i \right) + \left(\frac{\sum_i^3 rbc_{kl}^{E(i)}}{\sum_i^3 rbc_{kl}^{C\max(i)}} + \frac{\sum_i^n rbc_{kl}^{E(i)}}{\sum_i^n rbc_{kl}^{C\max(i)}} \right) \right) \tag{4}$$

In formula (4) E – means estimated value, C- constant, n is a number of observed links ahead of signal head. Taking into account the transportation capacities of subsequent segments of the network down the connection tree in the road network (from the traffic light location to *n-th* link) cannot be carried out indefinitely due to the dynamics of the traffic within the network. In the Formula (3) and (4) the applied weights for the saturation rate and the road network capacity ahead of an intersection were assumed as 50-50 ratio (arithmetic mean). In case of the existing ATCS systems such as SCOOT or SCATS these may seem to be identical yet in fact they are not. In the proposed system the object of optimisation is also a part of a section of a traffic lane located directly ahead of the traffic light (not only before signal head). In this approach we observe an empty space volume - not traffic flow characteristic. In this sense it may be expected that the proposed system offers a higher compression rate (the rate of filling a lane with vehicles) than in case of SCOOT and SCATS systems. In this sense this particular measurement may be called a reverse signal control.

3. Final remarks

The proposed method of modification of traffic control systems algorithms uses an extended logic of control of traffic signal control systems. The essence of this modification is that in the place of a classic control the characteristics of the road network are accounted for. One may say that the control algorithms have been made to cover the whole available area of a road network. An implementation of such a control system is basically limited to doubling the detection subsystem. In practice, in the traffic control systems this means an increase of the operational cost and the cost of installation of control systems by a few up to 10-20%. Such an increase in expenditure should be preceded by a thorough cost and benefit analysis (BCA). The costs and benefits will certainly be dependent on the quality of the traffic detection system. At present the area control systems often operate with the KPI at the level of 0.9[-] (ca. 90% utilisation of the weakest elements of the system). It may therefore be expected that even an increase of the utilisation of the network capacity by a single percentage caused by applying the proposed reverse line logic control concept is worth considering.

Another issue is related to the consequence in the implementation of the policy of sustainable development of the transportation. For example, the dedicated lanes for public transportation are important elements of this policy. In practice, such a solution is beneficial as this type of modal split related to the road network space leads to the unification of the traffic structure at the specialised lanes. As a result, the road network capacity at the selected lanes may be credibly estimated. On the other hand, the traffic lanes specialised from the modal split perspective induce the organisation of the road network which is not rational from the point of view of the total road network capacity. The proposed methodology contributes to the resolution of this issue. Within the proposed approach a non-utilised PuT lane ahead of a traffic light may be utilised and taken into consideration by the control system. This requires inclusion in the discussion the schedules of the PuT in a specific road network in co intersection with the real time location monitoring (which is an existing functionality of an ITS architecture, such as described by these authors in their proposal of utilising the GSM/GPS systems). The proposed methodology not only complements the activities in the domain of transportation balancing as to the rational modal split and a rational utilisation of a road network capacity.

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